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Coupled Chemistry-Meteorology: Simulations at 2.5km Resolution

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International Workshop on Air-Quality Forecasting Research

How particles affect the weather

- Particles scatter and absorb light.
  - This changes the balance between incoming solar radiation and outgoing infrared radiation, in turn changing the weather → **Aerosol Direct Effect.**
- Particles help form clouds.
  - Water molecules can condense on particles
  - The amount of condensation depends on particle composition
  - If conditions are right, the liquid water on and in a particle ***grows*** until the particles reach cloud droplet size
  - Particles thus may act as **Cloud Condensation Nucleii (CCN)**
  - The *location* of aerosols, and their *composition*, may thus influence where clouds form.
  - Clouds may also influence the balance between incoming solar radiation and outgoing infrared → **Aerosol Indirect Effect.**

Air-Quality Model Evaluation International Initiative, Phase 2 (AQMEII-2): A multi-model intercomparison of fully coupled AQ-Wx models.

See August issue 2015 of *Atmospheric Environment* for details

- Using feedbacks can improve the accuracy of forecasts of both weather and air pollution, *however*…
- The differences between models are often larger than the differences between a given model with or without feedbacks.
- These effects of feedbacks are not random: the differences between feedback and no-feedback simulations vary systematically in time and space.
- The models can be used to examine the direct and indirect effects *separately* – the indirect effect has the larger impact on forecasts.
- The effects are strongest close to large sources of pollution***: cities, forest fires, large industrial facilities***.

➔ **<u>Air pollution is affecting the weather.</u>**

➔ Models which **<u>accurately</u>** include feedbacks will do a better job than models which do not include feedbacks.

AQMEII-2 Effects of feedbacks: weather (Temperature, North America)

Makar et al, Feedbacks between Air Pollution and Weather, Part 1: Effects on Weather, Atm Env., 2015

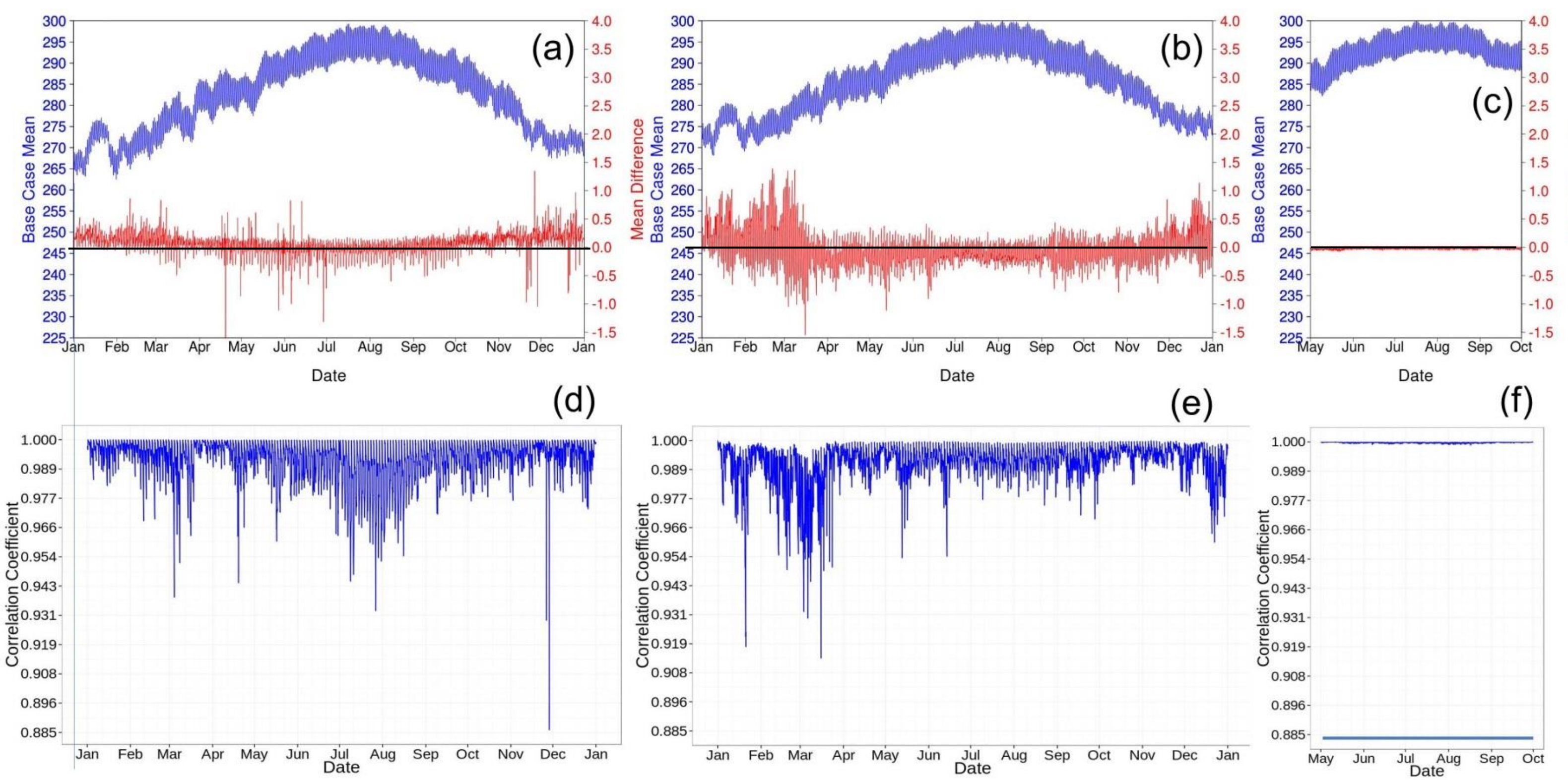
Effects on Temperature, North America: winter mean temperatures *increase* (direct+indirect effect models)

2010 NA

GEM-MACH (direct + indirect) | WRF-CHEM (direct + indirect) | WRF-CMAQ (direct)

No-Feedback grid-mean temperature, mean difference (feedback – no-feedback)

Hourly R^2 between feedback and no-feedback runs

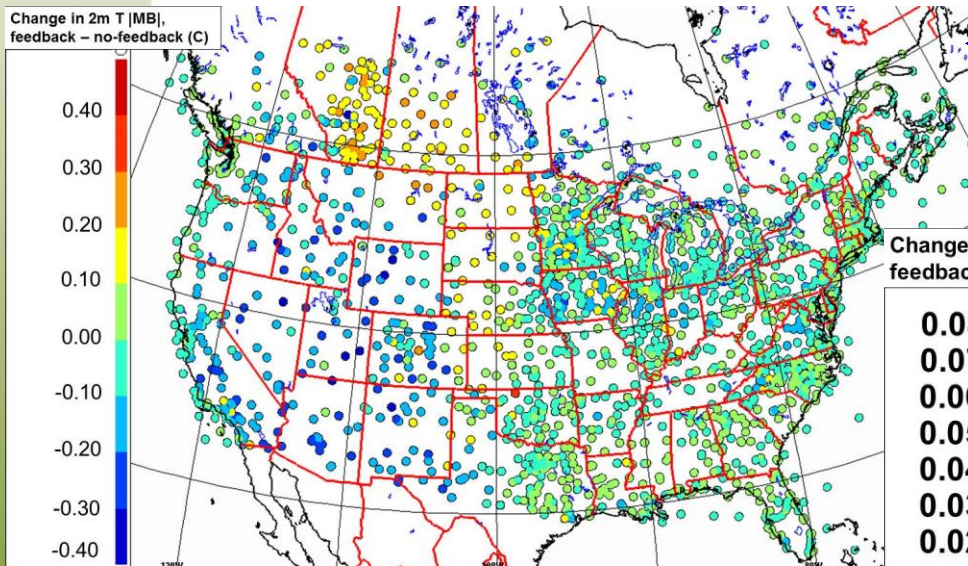


AQMEII-2 example: Annual Temperature

Makar et al, Feedbacks between Air Pollution and Weather, Part 1: Effects on Weather, *Atm Env.,* 2015

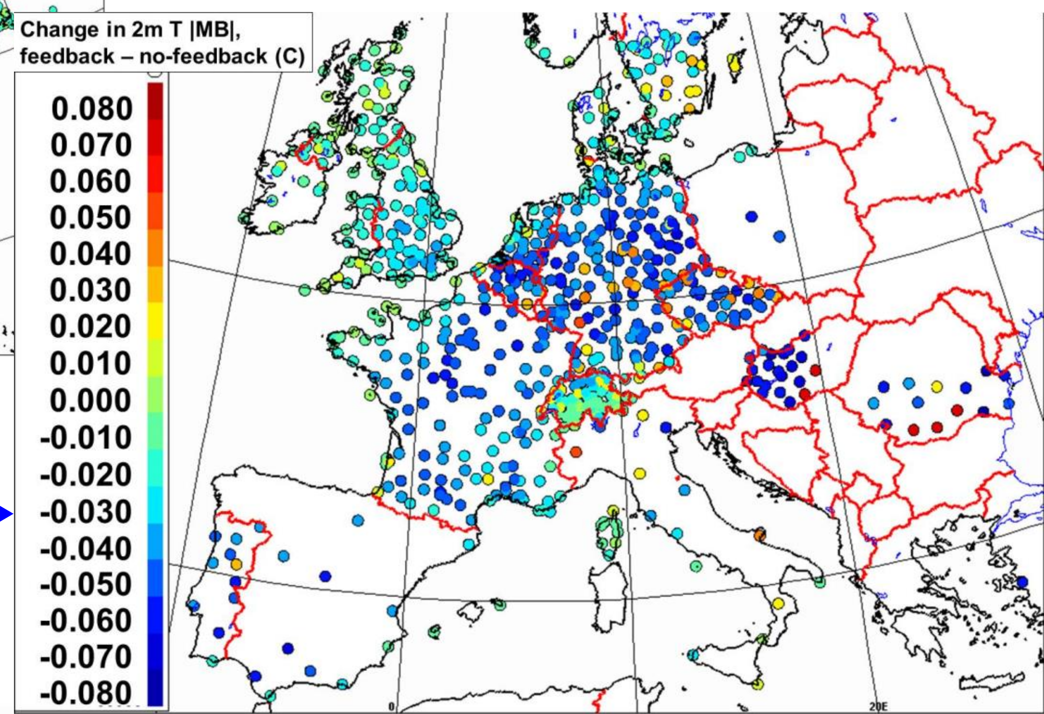
Change in magnitude of annual surface temperature mean bias compared to observations (feedback |MB| - no-feedback |MB|), North America and Europe, for the year 2010.

[-ve means improvement; +ve means deterioration]



GEM-MACH model, direct and indirect effects: temperature forecast bias ***improves*** over most of North America.

WRF-CHEM: direct effect only simulation: temperature forecast bias ***improves*** over most of Europe.



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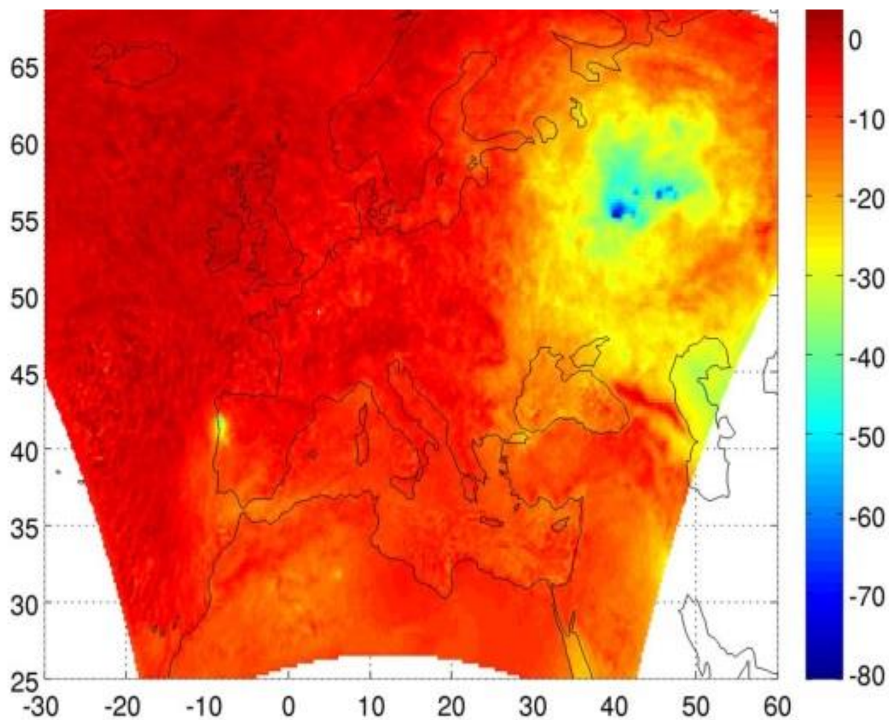
AQMEII-2 Example: Summer Shortwave Radiation and Temperature

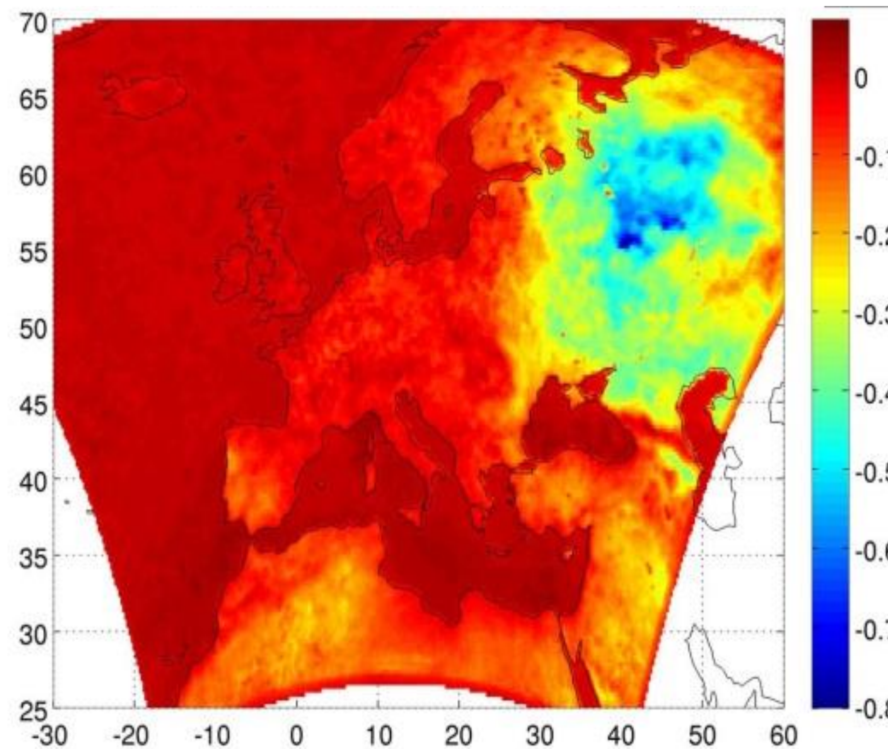
Makar et al, Feedbacks between Air Pollution and Weather, Part 1: Effects on Weather, *accepted*, Atm Env., 2014

- WRF-CHEM Direct Effect only simulation: July 25th to August 19th, 2010, EU domain.
- Large forest fires in Russia result in BIG decreases in surface downward shortwave radiation and temperature. Which in turn changes the atmospheric stability, changing the plume rise, etc…

Change in
Surface Downward Shortwave Radiation
(W m^{-2})



Change in
Surface 2m Air Temperature (C)



What about more local changes?

- AQMEII-2:
  - Makar *et al* + many more papers by collaborators in AQMEII-2 → August 2015 issue of *Atmospheric Environment*
  - Showed that the effects of feedbacks between weather and air pollution are the strongest in areas with high emissions.
  - Looked at weather across the continent (North America and Europe). What about more local changes?
  - Used models with a horizontal resolution of at best 12 km. What differences in the predictions might be seen with higher resolution models?
- Using a higher resolution model allows better coupling of the feedback processes for cloud formation.
- A higher resolution model can also be used to show the local effects of feedbacks between weather and air pollution.

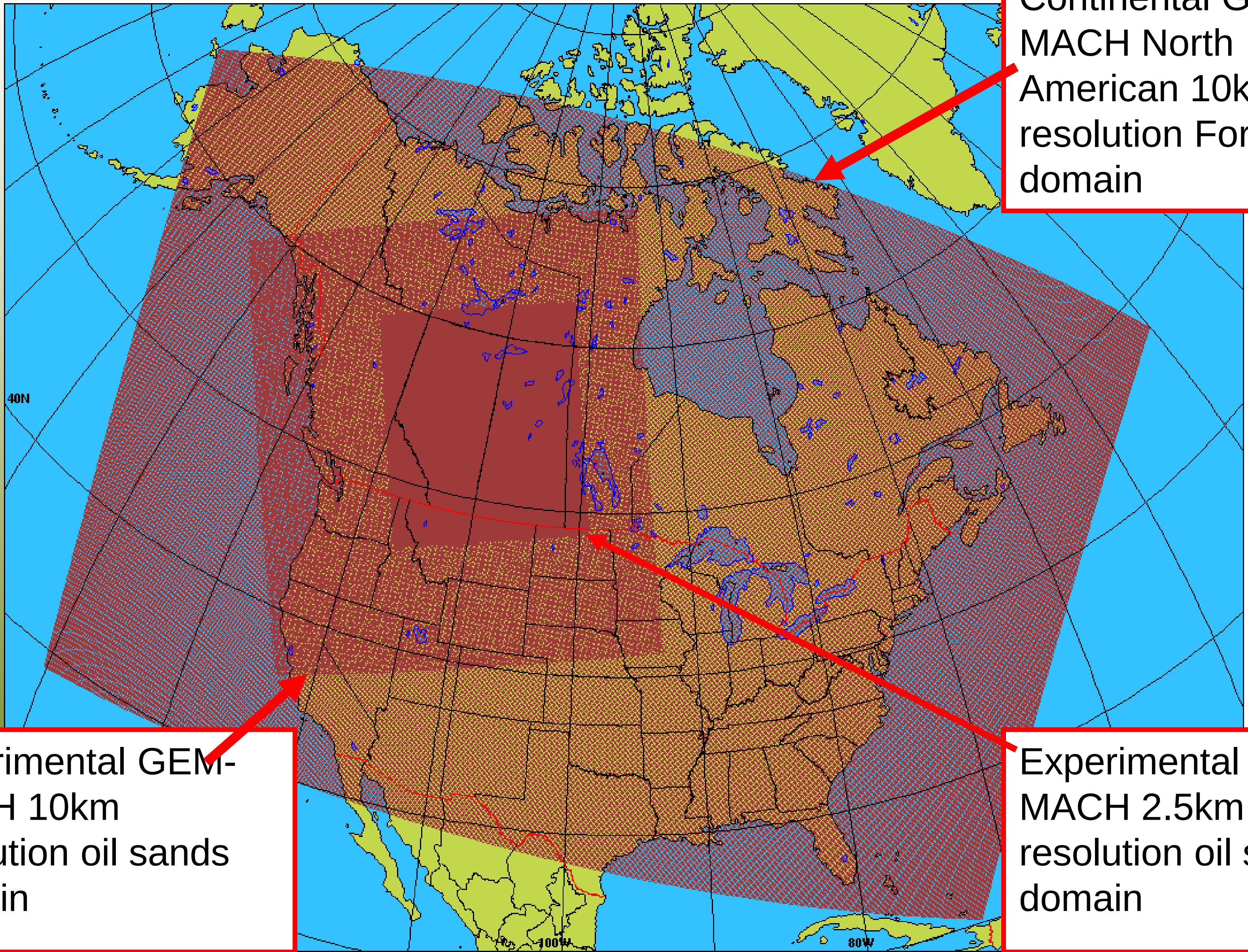
Initial Work at High Resolution

- Nested simulations for the Canadian provinces of Alberta and Saskatchewan, highest horizontal resolution: 2.5km.
- Period:
  - August 10, 2013 to September 8, 2013.
  - Corresponded to a joint Canada/Alberta monitoring intensive in the region of the Canadian Oil Sands (more data available for comparison to model simulations).
- Model: the feedback version of Environment Canada's Global Environmental Multiscale – Modelling Air-quality and CHemistry (GEM-MACH). Includes updates since AQMEII-2
- **Compare the highest resolution model results to observations: *are the forecasts improved using feedbacks?***
- **How does air pollution affect weather and vice-versa, *locally*?**

Nesting Setup

- Overlapping runs at successively higher resolution used
- A “backbone” no-feedback run is used as the starting point for 3-level nested runs down to 2.5km resolution.
- Three sets of nested runs: *No-Feedback*, *Direct Effect*, *Direct&Indirect Effects*.
- The resulting 24 hour 2.5km forecasts are “stitched together”
- Differences created of the average of hourly output:
  - *Direct Effect – No-Feedback*
  - *Direct & Indirect Effects – No-Feedback*
  - *Direct & Indirect Effects – Direct Effect*
- Both runs were compared to surface observations of air pollution (AIRNOW, here).

Nested domain: 3 levels of nesting



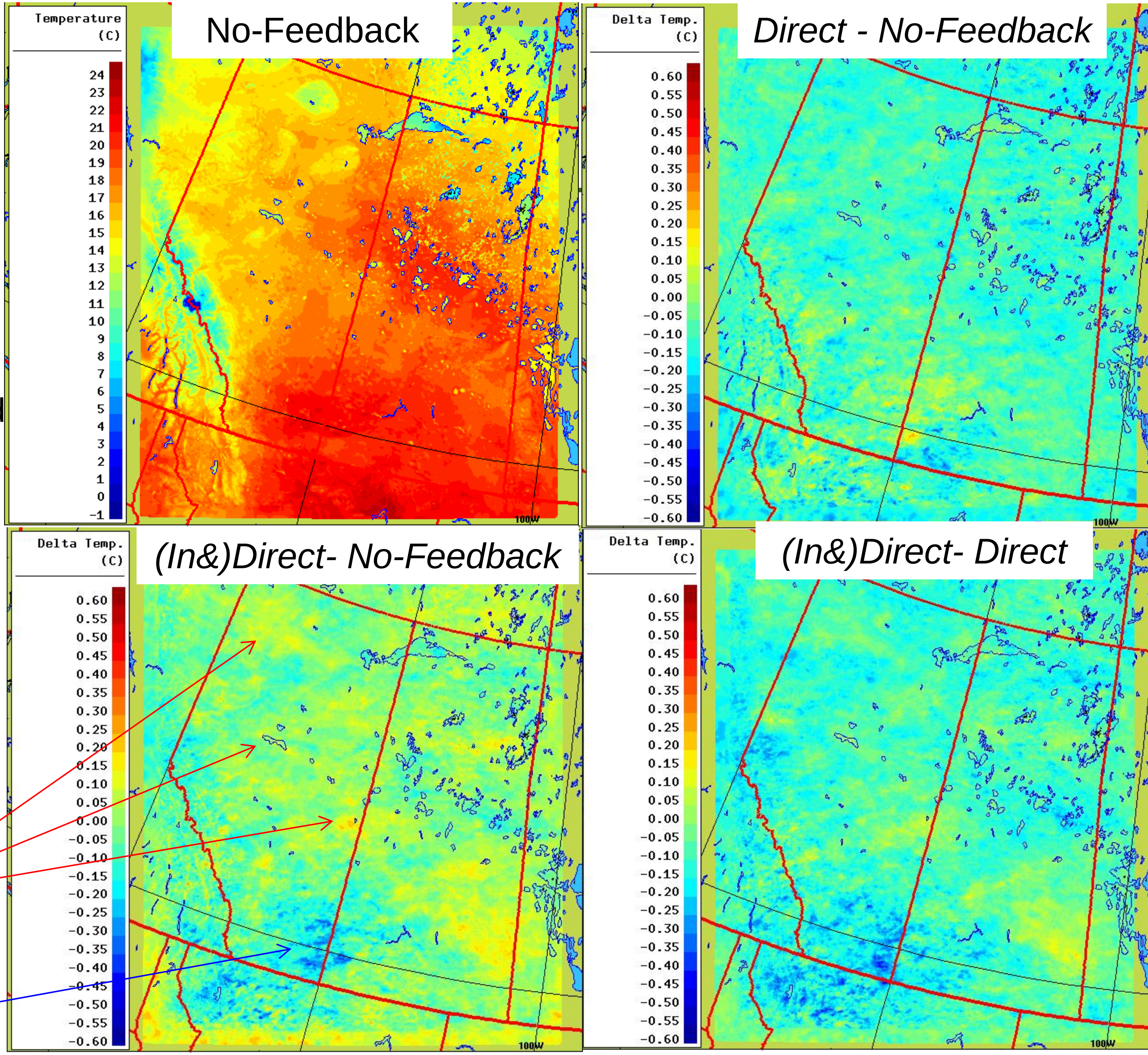
Continental GEM-MACH North American 10km resolution Forecast domain

Experimental GEM-MACH 10km resolution oil sands domain

Experimental GEM-MACH 2.5km resolution oil sands domain

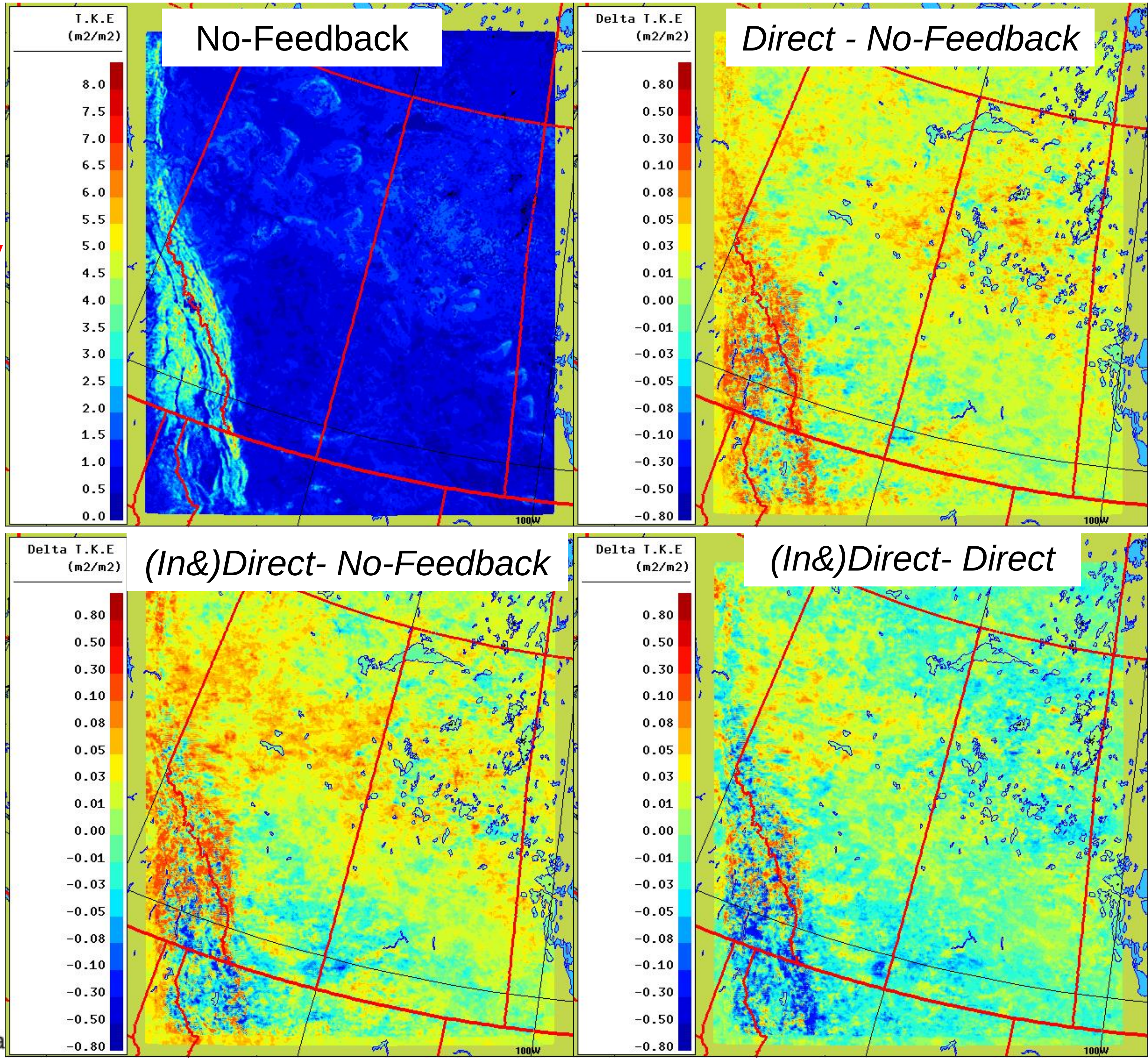
Nested Model results: Average Temperature (C), No-Feedback and *Differences*

Both positive and negative variations due to adding the feedbacks. Combining the direct and indirect effects increases temperatures over much of the domain (+0.25C). Decreases in southern Alberta -0.25 C).



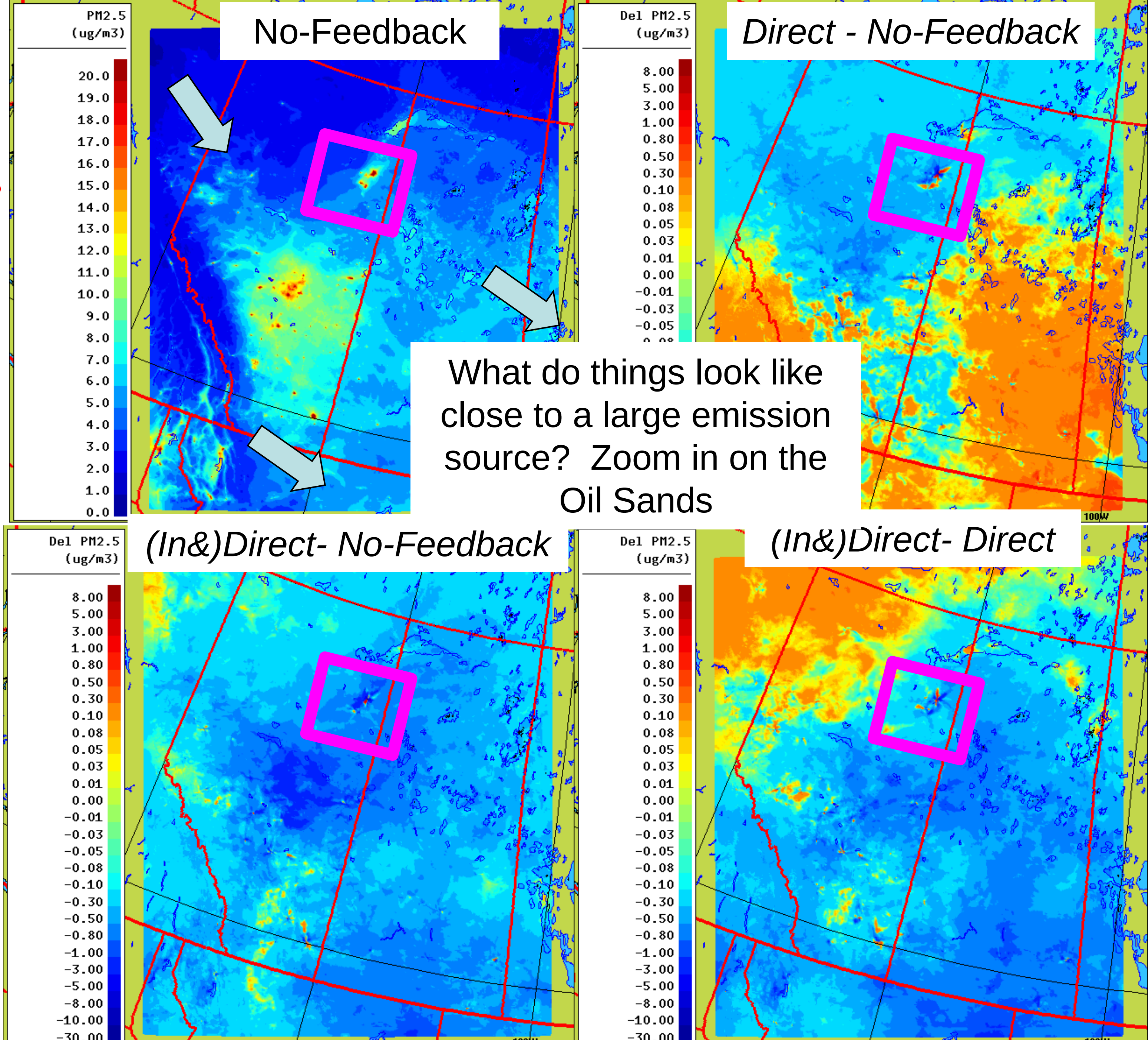
Nested Model results: Average Turbulent kinetic energy ($m^2\ s^{-2}$), no-feedback and differences.

The surface TKE is increasing over much of the domain, mostly driven by the direct effect, some increases associated with indirect effect in northern Alberta.

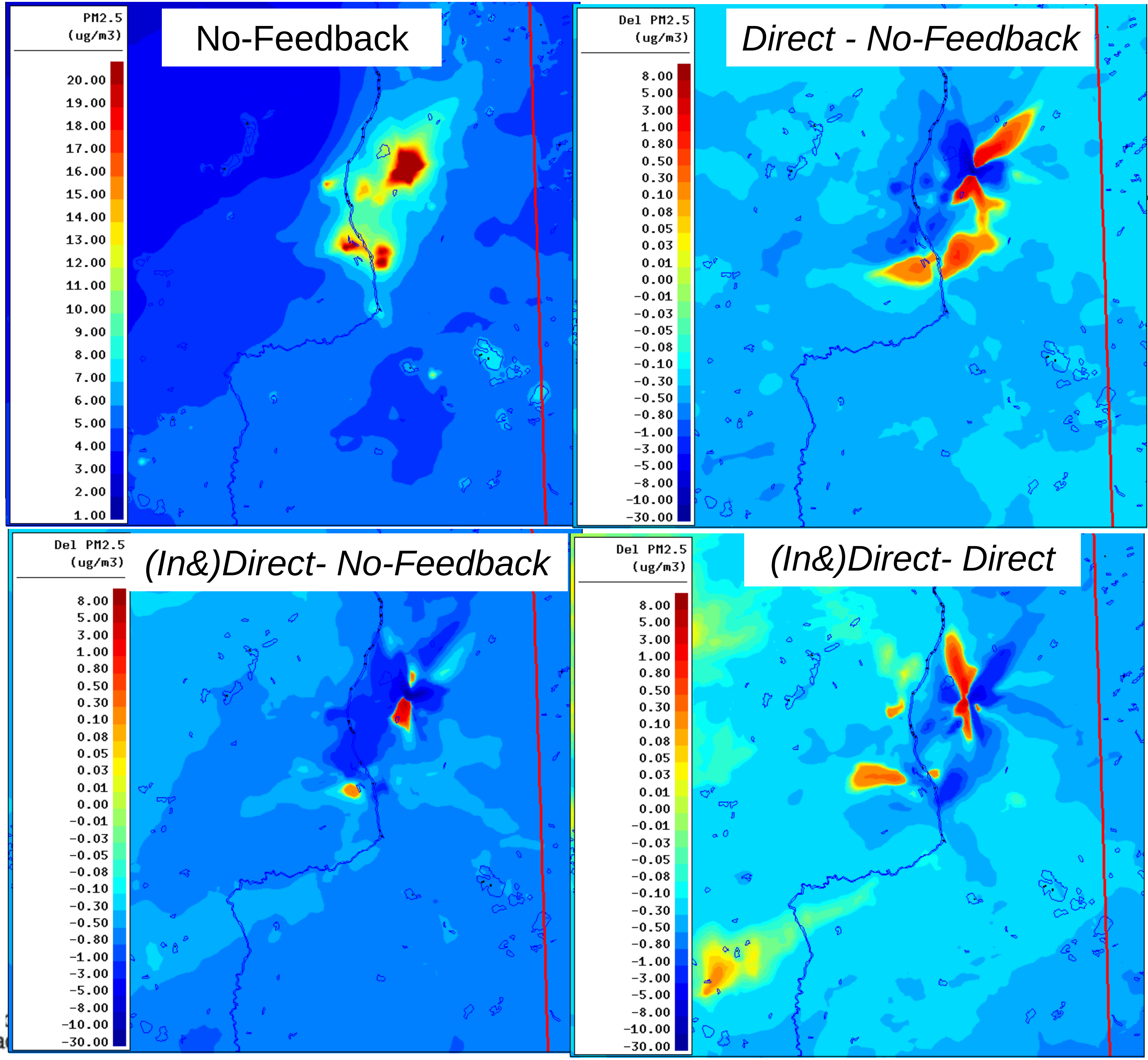


Nested Model results: Average $PM_{2.5}$ ($\mu g\ kg^{-1}$), no-feedback and differences

An example of competing processes: the direct effect **increases** the $PM_{2.5}$ in the SW and SE of the domain (downwind of the sources), while the indirect effect increases NE (upwind) $PM_{2.5}$ and **decreases** it in all downwind



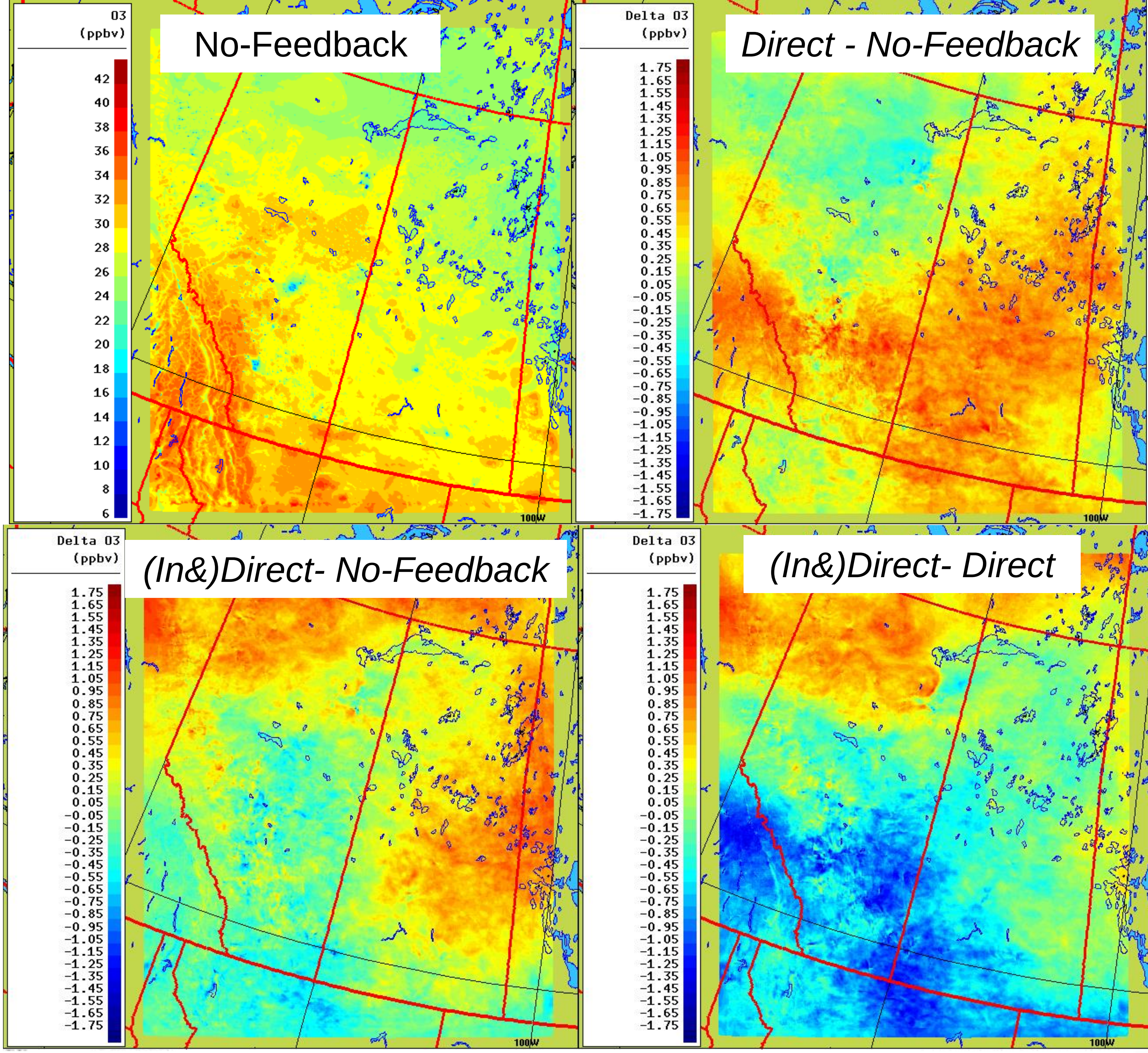
Nested Model results: Average $PM_{2.5}$ ($\mu g\ kg^{-1}$), no-feedback and feedback and differences: Close-up for Oil Sands region.



Positive and negative difference fields are associated with local changes in the plume direction. **Both** feedbacks are decreasing $PM_{2.5}$ relative to the no-feedback run.

Nested Model results: Average O_3 (ppbv), no-feedback and differences.

The direct effect decreases O_3 near the Oil Sands, and increases it downwind. The Indirect effect increases O_3 in the north, decreases it in the south (reducing some of the increases due to the direct effect.

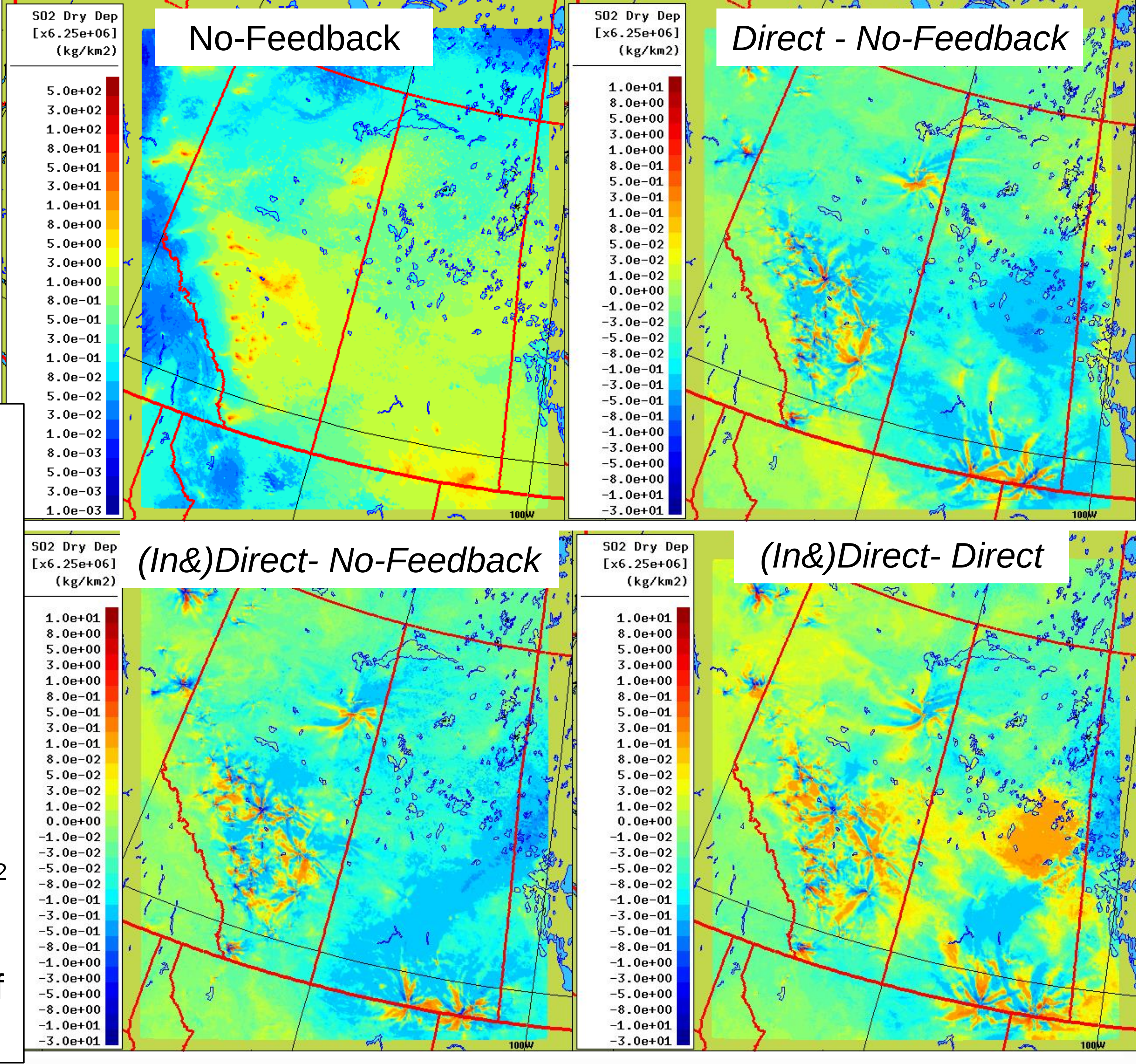


Nested Model results near the oil sands: top row: average cloud liquid water content (g/kg), > 1.2×10^{-5} kg/kg, and bottom row: difference field for >5×10^{-6} kg/kg → *Indirect Effect is increasing cloud cover.*

Nested Model results: Average SO_2 dry deposition (kg km^{-2}), no-feedback and differences.

➔ Close to the sources, the feedbacks change the plume direction, hence its local deposition.

➔ Downwind, however, they result in overall result in overall decreases in SO_2 dry deposition (perhaps due to more oxidation of SO_2 by clouds).



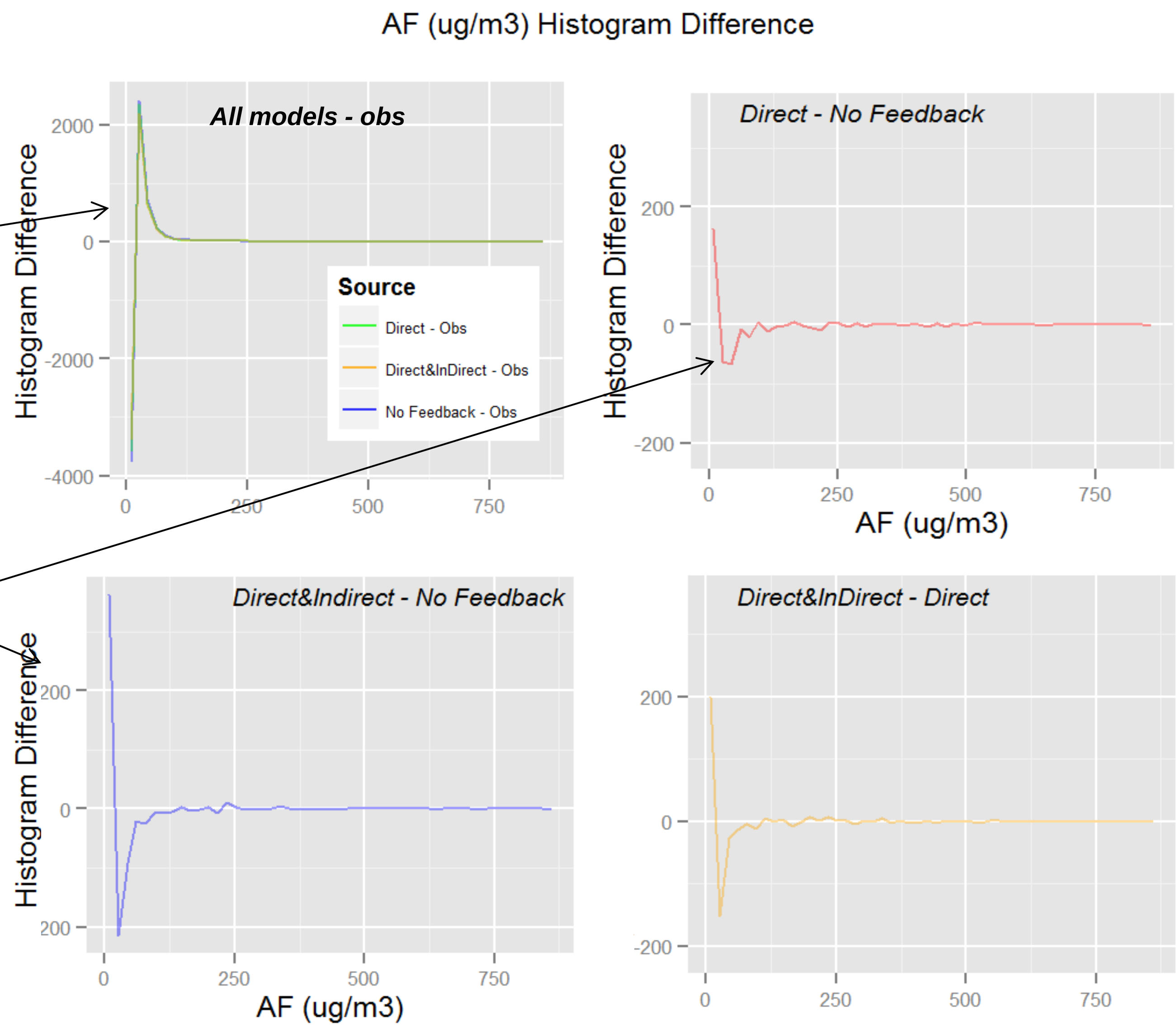
Statistics: how did feedbacks affect the model results (chemistry)? Oil Sands stations

White: no change. Green: best score Red: Worst score Yellow: Middle or tied.

Stats.	$PM_{2.5}$ (μgm^{-3})			NO_2 (ppbv)			O_3 (ppbv)		
		Feedback			Feedback			Feedback	
Model	Base	Direct	Full	Base	Direct	Full	Base	Direct	Full
Num. of obs.	5530			5281			3557		
Frac. of predictions (FAC2)	0.54	0.54	0.52	0.34	0.34	0.35	0.69	0.70	0.68
Mean Bias	1.82	1.36	0.94	2.94	2.87	2.73	7.52	7.36	7.53
Mean Gross Err	5.42	5.31	5.18	5.54	5.51	5.36	9.99	9.53	10.03
Norm. Mean Bias	0.29	0.22	0.15	0.79	0.77	0.73	0.40	0.39	0.40
Norm. Mean Gross Err	0.87	0.85	0.83	1.49	1.48	1.44	0.54	0.51	0.54
Root Mean Sq. Error	9.81	9.74	9.35	10.55	10.85	10.37	14.71	13.51	14.13
Corr. Coef.	0.24	0.20	0.23	0.33	0.33	0.33	0.50	0.55	0.48

Are the Statistics *Systematic? Significant?* Histograms showing the Change in Frequency Distribution at observation stations: $PM_{2.5}$

It's difficult to see the change in the differences in frequency distribution residual (model – obs) between the different model versions.



However, you can see that the feedback simulations reduce the magnitude of the differences from the obs – they are opposite in sign from the model-obs differences.

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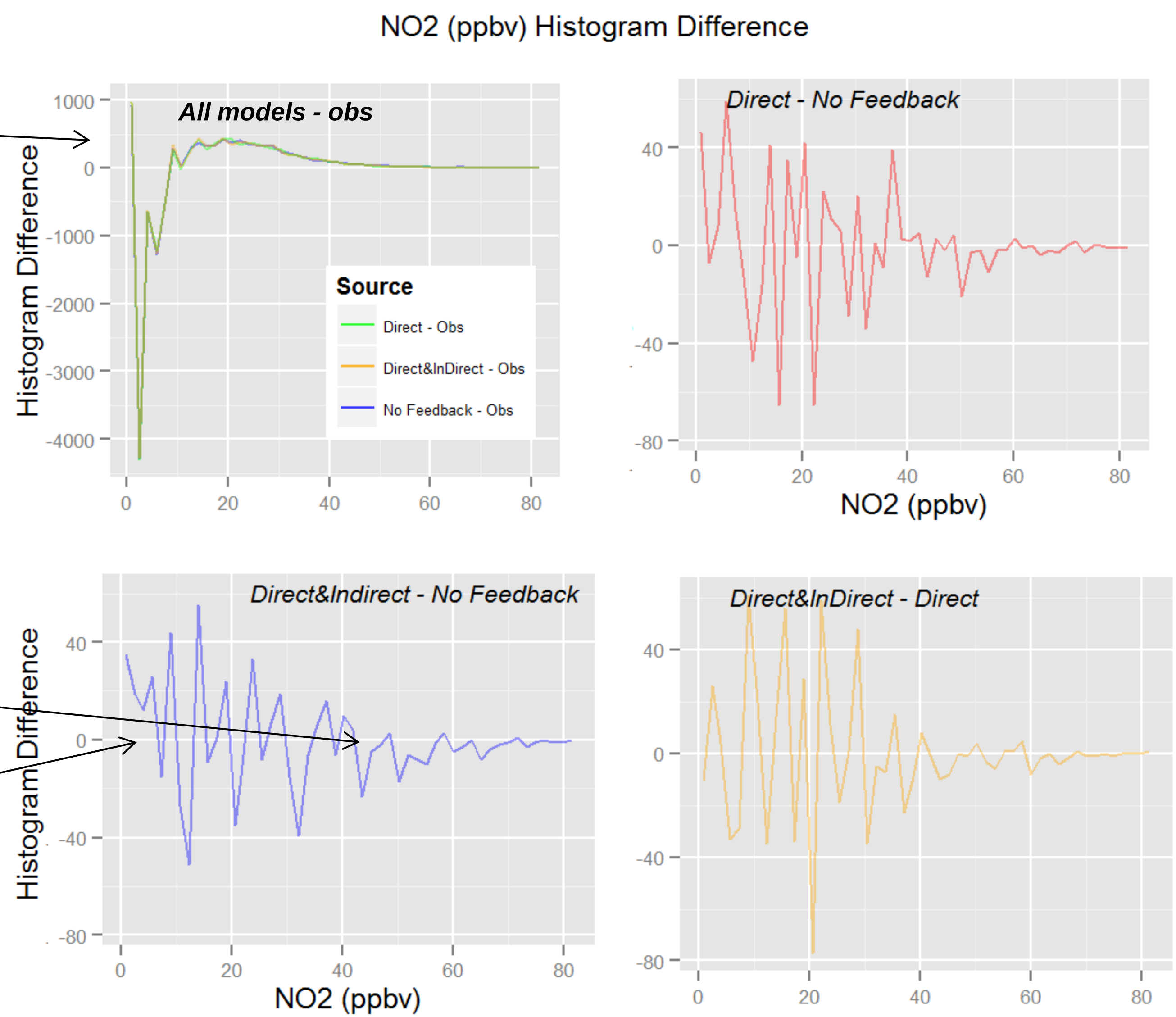
Are the Statistics *Systematic?*
Histograms showing the Change in Frequency Distribution at observation stations: NO_2

Model (all versions) are biased high between 10 and 60 ppbv, and biased low between 1 and 10 ppbv



The feedback models reduce the positive bias between 40 and 80 ppbv, and reduce the negative bias from 1 to 10 ppbv – but are pretty noisy from 10 to 40 ppbv.

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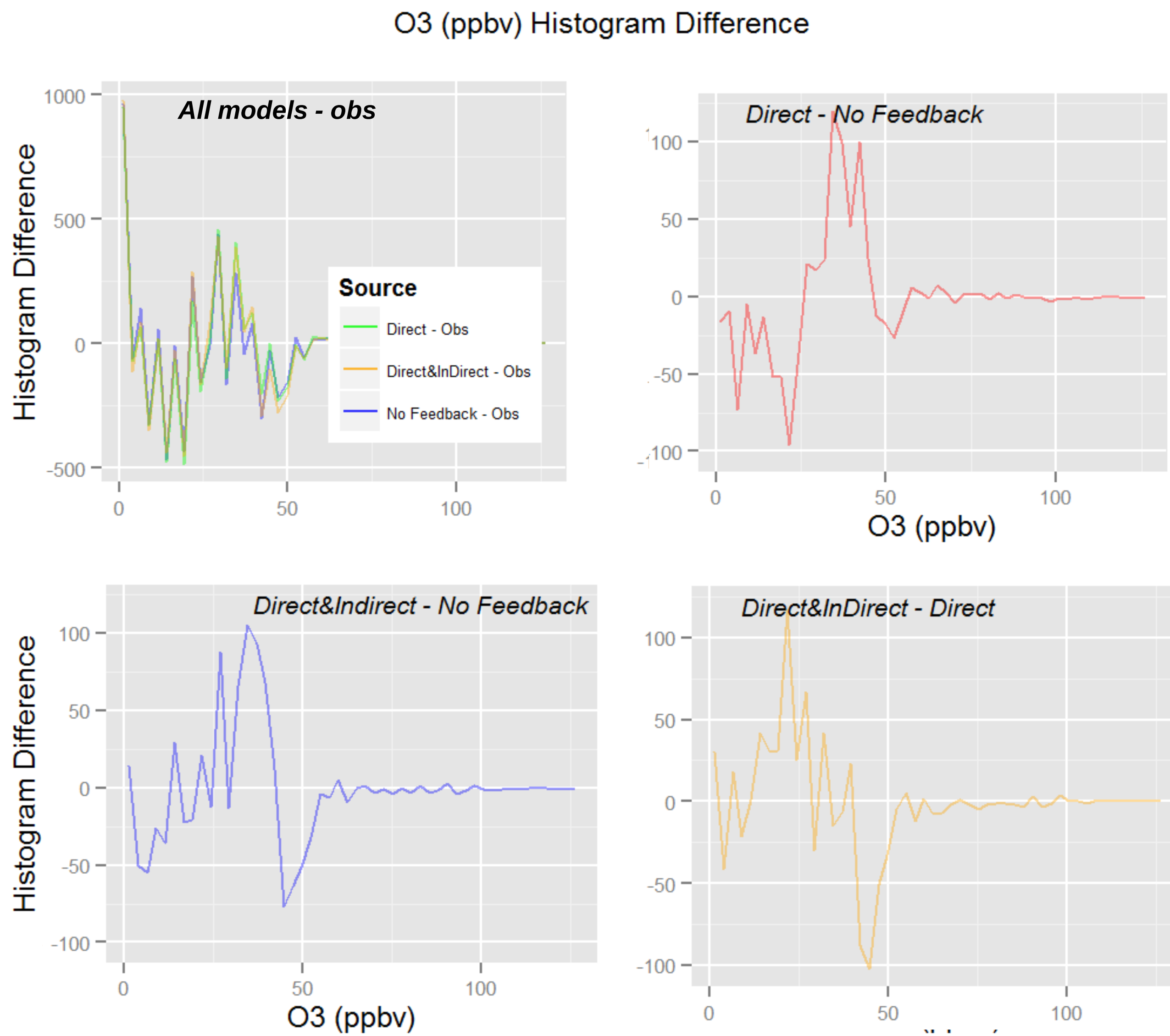
Are the Statistics *Systematic?* Histograms showing the Change in Frequency Distribution at observation stations: O_3

For O_3, the model – obs histogram differences are very noisy – need a longer time series for comparison.



The performance between the models was a bit of a toss-up; the feedbacks are changing the O3 response, but not consistently towards model improvements.

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Conclusions (high resolution simulations)

1. Air pollution is affecting the weather (and vice versa) on the high resolution domain.
2. The effect is *smallest for O_3, larger for NO_2, largest for $PM_{2.5}$* (a one-month summer simulation is close to the limit for what can be discerned from histogram analysis).
3. Plume altitude and direction changes seem linked to turbulence and wind direction changes.
4. Ozone changes seem linked to changes in cloud cover.
5. The addition of both feedbacks improves stats for $PM_{2.5}$, NO_2.
6. Adding the direct effect feedback improves O_3, but the further addition of the indirect effect degrades O_3.
7. Feedbacks change the pattern of downwind deposition.
8. Effects can be seen both close to the emission sources and far downwind (deposition).

Next Steps

- Colleagues Sylvie Gravel and Mike Moran have created a new version of GEM-MACH based on the next generation of the GEM weather forecast model: GEM-MACHv2.
- The above simulations were done with version 1.5.1 of GEM-MACH – the same changes have been ported to GEM-MACHv2 by Ayodeji Akingunola, and the simulations are being repeated.
  - Do we get the same results with the new model?
- Other domains: PanAm Games
  - How do feedbacks affect AQ forecasts for a city of 3 million people?
  - GEM-MACHv2 was used for AQ forecasting for Toronto (Craig Stroud), with mobile laboratory observations (Jeff Brook).
  - In one of the follow-up studies for PanAm domain, Paul and Wanmin Gong will be expanding on the feedback work, using GEM-MACHv2.

Thanks for your interest!